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Carbon Pathways in the Global Gas Market: An Attributional Lifecycle Assessment of the Climate Impacts of Liquefied Natural Gas Exports from the United States to Asia

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Abstract: While the United States is poised to become a major exporter of liquefied natural gas (LNG), relatively little attention has been paid to greenhouse gas emission impacts from exporting US natural gas to Asia, a key likely destination. Using bounding scenarios of attributional lifecycle analysis, this study finds that the climate impacts of US exports to China, Japan, India, or South Korea could vary significantly, with annual global lifecycle emissions ranging from -88,000 metric tons CO₂e to +170,000 metric tons CO₂e per Bcf of exports. Exact emissions will depend on factors such as (a) the final end-use of the LNG, (b) domestic market impacts from increased natural gas prices in the U.S., (c) induced additional energy consumption in importing countries, and (d) methane leakage rates. Country specific GHG outcomes can differ from global GHG outcomes, with major implications for extraction and consumption based emissions accounting. The study's results indicate the need for more robust consideration of the climate impacts of all energy exports in terms of country specific energy analyses, global climate regulations, and market uncertainty. Thus, how gas is governed becomes of critical importance, for it will determine whether LNG is a net sink or source of additional emissions.

Keywords: liquefied natural gas (LNG); LNG trade; energy exports; methane leakage; lifecycle analysis (LCA); attributional lifecycle analysis (ACLA)

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Nomenclature

ALCA = attributional lifecycle assessment

BCF = billion cubic feet

CLCA = consequential lifecycle analysis

CO₂e = carbon dioxide equivalent

DOE = U.S. Department of Energy

FERC = U.S. Federal Energy Regulatory Commission

GWP = global warming potential(s)

LCA = lifecycle assessment

LNG = liquefied natural gas

TCF = trillion cubic feet

U.S. = United States

Yr = year

1. Introduction

A dramatic and rapid rise in natural gas production resulting from the hydraulic fracturing of shale gas has quickly but substantially changed the energy landscape of the United States. In 2017, surging natural gas production due to the shale revolution led the United States to being a net exporter of natural gas for the first time in sixty years. (1, 2) While growing pipeline exports to Mexico and Canada were a partial cause, the beginning of large-scale liquefied natural gas (LNG) exports played a chief role in this reversal. Since 2005, advances in shale technology have led to US dry natural gas production increasing by more than 60%, leading to significant decreases in natural gas prices and a shift away from domestic coal power.

(3, 4) Originally faced with the prospect of having to import large amounts of liquefied natural gas, the US is now a LNG supplier.

Burgeoning production and low realized prices are behind mounting pressure from industry and legislators to export natural gas to other countries. LNG terminals with a cumulative capacity of more than 40 Bcf/day (>50% of the US domestic market) have received or are awaiting approval from the Department of Energy (DOE) and the Federal Energy Regulatory Commission (FERC) for permission to construct and operate facilities to export natural gas to countries without Free Trade agreements. (5) Projects with a combined capacity of more than 10 Bcf/day received all required approvals and are now under construction, with the first LNG exports beginning in early 2016. (6) With global LNG trade at 236.8 million metric tons in 2013, exports could increase global LNG trade and make the U.S. one of the largest LNG suppliers in global markets. (7)

Considering the potential size of U.S. LNG export terminals, the climate impacts of U.S. LNG exports could be large. During liquefaction, natural gas is cooled to -161 degrees Celsius, which condenses it into a liquid and allows transport to other countries by seaborne tanker. (8) LNG is turned back into a gaseous state in the importing country and stored or distributed into pipelines for use. The process of liquefying natural gas for transport can increase the carbon intensity of using natural gas. (9)

The domestic shift to shale gas has led to an abundance of research focused on affiliated lifecycle emissions and associated environmental impacts in the United States. (10-14) However, lifecycle assessment of international energy flows on a volume or project-level basis pose unique methodological challenges. Cross-boundary energy and other trade poses challenges in emissions accounting: extraction, production, and consumption emissions can differ significantly for

specific countries. (15) Most famously, the use of attributional LCA for corn ethanol led to a mistaken conclusion that ethanol would decrease greenhouse gas emissions; subsequent consequential studies demonstrated that the ALCA advantage of ethanol eroded due to global market GHG effects. (16) In evaluating the Keystone XL pipeline, the US State Department found that the pipeline was unlikely to increase global greenhouse gas emissions; critics, however, argued the analysis was flawed because of how it considered uncertain domestic and international market impacts. (17) When evaluating the lifecycle impacts of US coal exports, Bohnengal et. al. found that US coal exports to South Korea would decrease global greenhouse gas emissions. (18) However, this finding was a result of study boundaries confused international and domestic markets and accounting. (19) Most relevant to this article, multiple studies have examined the potential LCA impacts of exports from different countries, such as Australia, Qatar, or Canada (20-23). The applicability of these studies to the United States is limited as they are export oriented markets that do not face the same domestic market impacts US LNG exports might.

To date, only three major studies specifically assessed the broader climate implications of exporting LNG internationally from the United States. Skone et. al. performed an attributional lifecycle analysis of emissions of U.S. LNG delivered to Europe or Asia compared to Russian natural gas or regional coal for electricity generation. (24) Abrahams et. al. similarly assessed the lifecycle emissions of US LNG delivered to Europe or Asia; they expanded on Skone et. al. by examining lifecycle emissions associated with thermal energy use, performing uncertainty analysis, and conducting an initial scenario analysis of LNG replacing coal. (25) Both studies concluded that U.S. liquefied natural gas exports are likely to reduce global greenhouse gas emissions if they replace coal.

While critical first steps, these studies present an incomplete picture of the potential emissions impacts of U.S. LNG exports. Both studies make simplifying assumptions about the global coal generation fleet while neither examine the international market impacts of additional LNG sources and resulting lower energy prices. Abrahams et. al. (2015) discuss the potential domestic market impacts of LNG exports but do not quantify the interaction of domestic and international markets on emissions outcomes. Moreover, neither study considers how the energy policies and dilemmas of importing countries influence likely LNG end uses.

Gilbert and Sovacool (2017) built on these two studies by examining a broader array of end uses, evaluating emissions scenarios on a cross-sectoral basis, analyzing energy strategies of importers, and identifying the potential emissions impacts from domestic and international market outcomes. (26) This study expands on Gilbert and Sovacool (2017) by:

1. Reviewing the pros and cons of existing attributional and consequential lifecycle analysis when analyzing cross-border flows
2. Explaining the advantages and disadvantages of using bounding scenarios with ALCA to estimate global LCA emissions under uncertainty
3. Evaluating more domestic natural gas use cases and methane leakage scenarios
4. Quantifying how LNG trade causes changes in global emissions accounting such that global emissions outcomes can differ significantly from individual country outcomes

We present bounding scenarios based on an attributional lifecycle analysis that estimates the potential global emissions outcomes resulting from likely LNG end-uses in four Asian countries (China, Japan, India, and South Korea).

2. Literature Review of Lifecycle Analysis Methods

Attributional lifecycle analysis (ALCA) is a useful tool to quantify the total emissions impacts from different energy decisions. (27) By tallying up emissions from the entire lifetime of an energy source, an attributional lifecycle analysis allows for an initial look at what happens when average energy sources are changed. ALCA is useful to identify where supply chain emissions can be reduced and as to gauge the climate impacts of a policy or market change. (28) Using ALCA, both Skone et. al. and Abrahams et. al. concluded U.S. LNG exports would decrease global greenhouse gas emissions by replacing coal.

However, ALCA has several critical weaknesses. It does not account for market outcomes resulting from policy actions. As an accounting method, it is unable to describe complex market interactions and other decision making, limiting its applicability in informing policy. (28) In this specific case, the ALCAs developed by Skone et. al. and Abrahams et. al. are relatively limited in that they are only narrowly addressing the one for one replacement of coal for natural gas. In reality, market impacts are a lot more complex, with exported LNG from the U.S. potentially replacing many sources of energy. Accordingly, their conclusions are limited in describing how U.S. LNG exports may change global emissions.

Although ALCA has limitations, there is a major alternative: consequential lifecycle analysis (CLCA). While ALCA is focused on accounting for emissions resulting from individual processes, CLCA is focused on estimating emissions changes resulting from market or policy decisions. Practically, this usually involves modeling of different scenarios to determine how emissions change between them. Compared to ALCA, CLCA is better able to indicate what the emissions outcomes of specific actions are.

CLCA has its own weaknesses. Most importantly, it is subject to significant uncertainties, including policy, market, and technology decisions. Further, CLCA can contribute the most when employing scenario modelling – this limits its results to a set number of defined policy or market scenarios. (29) This is because CLCA design is intended to measure specific market changes compared to baseline conditions – for example, what happens to net lifecycle emissions if the U.S. exports 2,000 Bcf per year. When significant uncertainty exists as to baseline conditions as well as likely export levels (as in this case), CLCA is limited in its ability to provide meaningful insights.

Another potential limitation with CLCA methods is the underlying use of an energy model. To calculate emissions outcomes, CLCA use energy models to represent market and policy decision making. However, outcomes from such models are dependent on many factors, including the choice of model, its design, and key technological and policy assumptions. (30) Trutnevyte (2016) recently found that cost optimization models (a key method in most models) may not reflect real world outcomes. (31) Similarly, Gilbert and Sovacool (2016) recently found that one of the most commonly used energy models struggles with renewable energy projections because of mistaken assumptions and model designs. (32) In many ways, the design and structure of CLCA “broadens and changes the nature of uncertainty” for CLCA studies, creating stark contrasts with the seemingly more straightforward nature of ALCA accounting (33).

3. Research Design and Methods

The section describes our overall methodology of using attributional LCA scenarios to bound emissions outcomes, how we developed ALCA estimates, how we treated international and domestic market impacts in our scenarios, and how we treated uncertainty for methane

leakage from natural gas infrastructure. Additional information about our methods are included in Appendix I.

As a quick note, we only examine the potential range of global greenhouse gas emissions outcomes resulting from changes in U.S. LNG exports to Asia. This is only part of the overall picture needed to fully examine LNG exports – there are very large potential social and economic benefits and negatives that could accrue to both the United States and importing countries due to increased LNG trade from U.S. exports. These benefits and drawbacks are beyond the scope of this study. Further, we do not evaluate the LCA of US exports to other countries; Coleman et. al. found LNG exports to non-Asian countries likely increase global emissions due to a lack of coal displacement. (22) Our methodology would likely find a similar conclusion.

3.1. Designing attributional LCA scenarios for bounding

Although lifecycle analyses can be broadly sorted into two types (attributional and consequential), the reality is that existing methods often blur the lines between these two types of studies. (34) In particular, studies using ALCA often employ scenario analysis to estimate what real-world impacts would be in light of the ALCA (as Skone et. al. and Abrahams et. al. did). In this study, we used domestic and international market scenario analysis on top of an ALCA assessment in order to develop boundaries for potential emissions outcomes from U.S. LNG exports. Due to the relatively unexamined nature of U.S. LNG exports, it is unclear what uncertainties and factors scenario-specific CLCA studies should examine. By developing bounded scenarios using ALCA, we can better identify which factors are most likely to influence emissions, determine an estimated range of emissions outcomes, and guide future assessments.

Based on an examination of energy usage patterns in the United States and potential major Asian importers, we identified two major variables that will determine how U.S. LNG exports impacts global emissions: how LNG is used in importing countries and the domestic market impacts resulting from LNG exports. Based on identified end uses and likely domestic market impacts, we can then create scenarios of one-for-one replacement based on our functional unit. To put another way, we developed individual scenarios for each international and domestic market effect assuming that 1 Bcf of LNG is used at a rate of one-to-one with its effect (i.e. for electricity generation, electricity created from LNG equals the amount generated from coal). Our scenarios treat international and domestic market impacts separately. Once we have determined all potential emissions outcomes based on these individual scenarios (derived from ALCA estimates) we can then compare them to determine likely emission ranges and to identify factors that will influence outcomes.

Our method has several advantages. Significant uncertainty about energy prices, market outcomes, and policy leads to many potential CLCA outcomes depending on energy model design and assumptions. With so little work done looking at emissions impacts from LNG exports, our method allows us to identify the major factors that will influence emissions, which can then subsequently inform CLCA analysis to examine specific scenarios. The results of our method essentially creates a “bounding” or range representing a variety of different emissions outcomes. As long as the import of LNG does not cause energy consumption to increase more than the LNG supply and as long as the export of LNG does not reduce energy consumption by more than the amount exported, our scenario bounds would represent all potential emissions outcomes across multiple market, policy, and technical scenarios. Our method is intended to capture the range of most likely outcomes that result from uncertainty and variability in CLCA

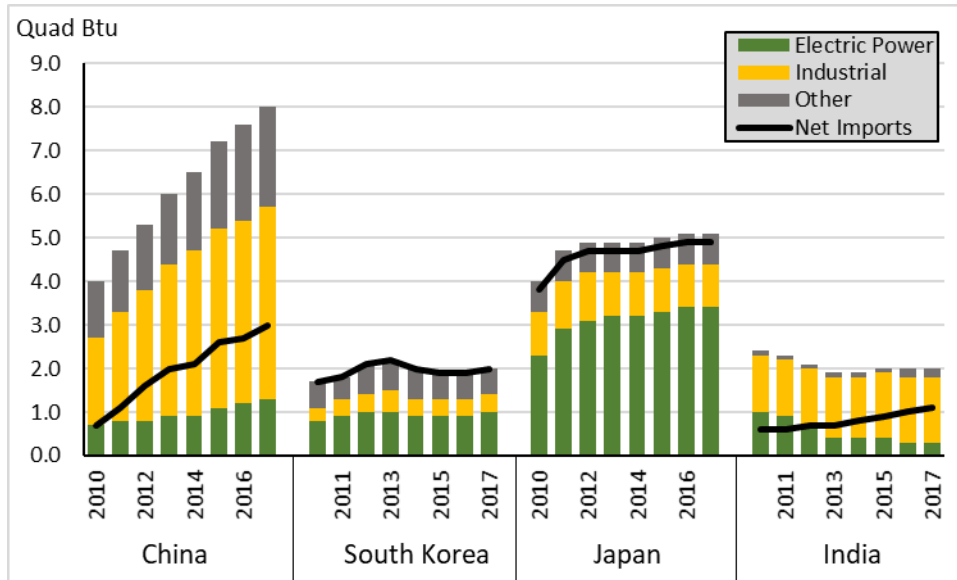
parameters. Finally, the bounding nature of our analysis and the functional unit enable our method to be applied to both general export volumes and to project-level analyses.

However, our method has several disadvantages. Most notably, unlike a CLCA, we do not use an energy model to measure market changes. We are only able to identify what factors will influence emissions outcomes and are not able to develop quantitative or qualitative likelihoods. Further, if the addition of LNG causes overall energy demand to increase by more than the addition of LNG (i.e. 1 Bcf of LNG imports drives more than 1 Bcf equivalent of new energy demand), our scenario bounds would not capture that market outcome. However, considering the general nature of elasticity in energy (particularly in the short term), such an outcome is unlikely.

3.2. Determining LNG end-uses to include or exclude from attributional LCA

To analyze the potential emissions impacts of U.S. LNG exports to Asia, we use the potential uses of LNG identified by Gilbert and Sovacool (2017) which were based on energy mixes and strategies of importing countries. We focused exclusively on four major importing countries: China, Japan, South Korea, and India. Figure 1 offers a high-level overview of natural gas trends in each country.

Figure 1. Natural Gas Demand and Import Trends in Japan, South Korea, China, and India



Source: IEA 2017

In total, we developed attributional lifecycle estimates for eleven different effects of U.S. LNG:

- Replacing coal generation specifically in China, Japan, South Korea, or India;
- Replacing oil-fired generation in Japan;
- Replacing coal used for thermal energy in any country;
- Replacing or preventing construction of nuclear reactors, solar energy facilities, or wind energy generation in any country;
- Or leading to additional natural gas generation or thermal energy use.

Notably, we did not include alternative natural gas supplies; in comparison, both Skone et. al. and Abraham et. al. considered the potential impacts of U.S. LNG compared to Russian natural gas. However, as this study is more narrowly focused on Asia, alternative natural gas supplies are limited. All four countries examined are large importers of natural gas and have not yet

developed significant natural gas supplies. With the exception of eastern China, none of the countries studied are likely to receive pipeline imports from Russia or other sources. It is possible that U.S. LNG will displace other sources of LNG, such as the Middle East or Australia. However, much of this existing natural gas supply is on long term contracts, displaced LNG is likely to be burned elsewhere (likely in another Asian country), and there are uncertainties regarding lifecycle LNG emissions for other sources. Critically, China has significant reserves of natural gas locked in shale; if these sources are drilled and infrastructure established, domestic Chinese natural gas could compete with imported LNG. (35) However, Chinese shale natural gas production has (so far) failed to materialize. Moreover, there is insufficient data to estimate emissions from Chinese shale production, particularly as it relates to uncertainty regarding methane leakage. In Appendix 1, we briefly discuss how the LCA profiles of alternative natural gas supplies would vary across suppliers and how our bounding methodology contains these outcomes.

There were several potential end-uses of LNG imports to major Asian importers that we identified but did not quantify in this study: LNG for chemical feedstocks, small cook stoves, or for vehicles running either LNG or compressed natural gas from LNG. We excluded these sources for two primary reasons: 1) we were unable to find reliable LCA estimates for these sources in importing countries and 2) these are smaller potential end-uses compared to other end-uses considered in this study. Next, we examined the major uses of natural gas in the United States to determine what ALCA estimates are needed to represent domestic market scenarios in the United States. The energy system in the United States is in the midst of significant change with natural gas and renewable generation rising rapidly, coal generation decreasing, and nuclear energy stagnant but struggling. Low natural gas prices and environmental regulations are posing

major limits on coal generation. Exporting LNG would have the effect of increasing natural gas prices, leading to six potential emissions effects that we developed lifecycle emissions estimates for:

- Increased natural gas production
- Increased coal, nuclear, solar, or wind generation
- Decreased natural gas consumption

Notably, the United States does not use significant levels of coal for industrial purposes.

To determine attributional lifecycle emissions for the potential uses of U.S. LNG internationally and domestically, we aggregated lifecycle estimates from multiple sources while developing several of our own. Unfortunately, unlike the United States and Europe, there are a limited number of lifecycle greenhouse gas estimates for emissions sources in our studied countries. (36) After normalizing electricity generation emissions into CO₂e per MWh and thermal energy emissions into CO₂e per MMBtu (HHV), we converted both into the amount that would be created by an equivalent amount of natural gas (measured by Bcf). Thus, Bcf was our functional unit.

In total, we calculated attributional lifecycle emissions estimates for eleven foreign end uses and six domestic market effects. For additional details about how these estimates were gathered and estimated, please see Appendix I.

3.3. Treatment of natural gas methane leakage

In the United States, recent studies have indicated that natural gas infrastructure may leak more methane than previously estimated by the US Environmental Protection Agency (EPA).

(10, 11) As methane is a more potent greenhouse gas than carbon dioxide, methane leakage potentially undermines the climate benefits of coal to natural gas fuel switching domestically and abroad. The precise amount of methane leakage remains uncertain. (13)

These variations, however, are critical as multiple studies have indicated that the ultimate level of methane emissions will impact climate outcomes from using natural gas. (49-14) With substantial uncertainty remaining, we test the impacts of different leakage levels on the LCA emissions of LNG exports by employing four leakage values: 0%, 1.5%, 3%, and 6%. These values represent a no leakage case, EPA estimates of methane leakage, and worst case methane leakage scenarios from Brandt et. al, modified to recognize the absence of distribution system leakage. This study does not explicitly account for methane leakage between LNG import terminals and final use; as per Skone et. al. and Abrahams et. al. we assume close proximity to LNG import facilities limits emissions.

3.4. Scenario analysis of international and domestic market impacts

Once attributional lifecycle estimates were developed for each of our identified uses of LNG, we use scenario analysis to bound potential domestic and international market impacts. We had two types of scenarios: one to represent international market effects and one to represent domestic market impacts.

For international market effects, we assumed a one-for-one replacement of the potential end-use by LNG for nine scenarios (coal for electricity generation in all four countries, coal for thermal use, oil for electricity generation, nuclear for electricity generation, solar for electricity generation, and wind for electricity generation). The result of these scenarios represent the

emissions outcomes if one functional unit of LNG (Bcf) were used to replace the identified end-use.

We also had two special international scenarios that deserve extra discussion: additional electricity use and additional energy use (thermal). These scenarios represent what would happen if LNG imports lead to increased consumption of natural gas through lower prices and do not displace other fuels. To put another way, both scenarios assume that all 1 Bcf of imported LNG is only used to meet energy demand that would not have occurred in the absence of LNG imports. These two categories “additional electricity/energy” are not intended to reflect non-related energy demand growth; rather they reflect the quantity demanded elasticity effects of additional natural gas supplies. If a country were to experience energy demand growth independent of LNG, our scenario method would treat that energy demand growth like any other type of energy. As we use a functional unit of Bcf, we are not measuring the absolute changes in emissions necessary to explicitly represent energy demand growth.

For domestic markets, we developed three general scenarios for U.S. LNG exports based on the notion that LNG exports would lead to increased natural gas prices. These elevated prices would lead to market impacts that functionally impact where the exported LNG came from: increased natural gas production (that would not have occurred in absence of LNG exports), replacement of natural gas for power generation by coal, nuclear, solar, or wind, and decreased natural gas consumption (that occurs solely due to LNG exports). Unless otherwise specified, our default for international scenarios assume that U.S. LNG exports come solely from reduced domestic consumption of natural gas.

When combined, these international and domestic market scenarios are intended to bracket the potential emissions outcomes – that is, determine the range of potential outcomes

resulting from different mixes of fuel switching, additional energy use, and domestic impacts. We do not use an energy model to calculate the specific effects of a certain LNG export levels due to substantial market and policy uncertainties. Small variations in price, technology, or policy assumptions readily influence the results of such an energy model while not providing effective policy guidance. Rather, our method is intended to encapsulate all potential market model scenarios by including all potential outcome spaces. By setting our functional unit as Bcf, we can determine what the maximum increase and maximum decrease from LNG exports for both volume and project-level analyses. For example, emissions would increase the most if all of the 1 Bcf of LNG exports came from increased natural gas production in the U.S. (resulting solely from the export of LNG) causing additional energy demand in importing countries (that would not have occurred otherwise). Conversely, in our scenarios, emissions would decrease the most if all 1 Bcf of LNG came solely from reduced natural gas consumption (resulting solely from the export of LNG) replacing the most emissions intensive end-uses in importing countries.

Notably, due to limitations in our emissions estimate sources and the need for simplification of estimating, we were unable to develop robust uncertainty bounds for most lifecycle estimates (we discuss the implications of this in the conclusion).

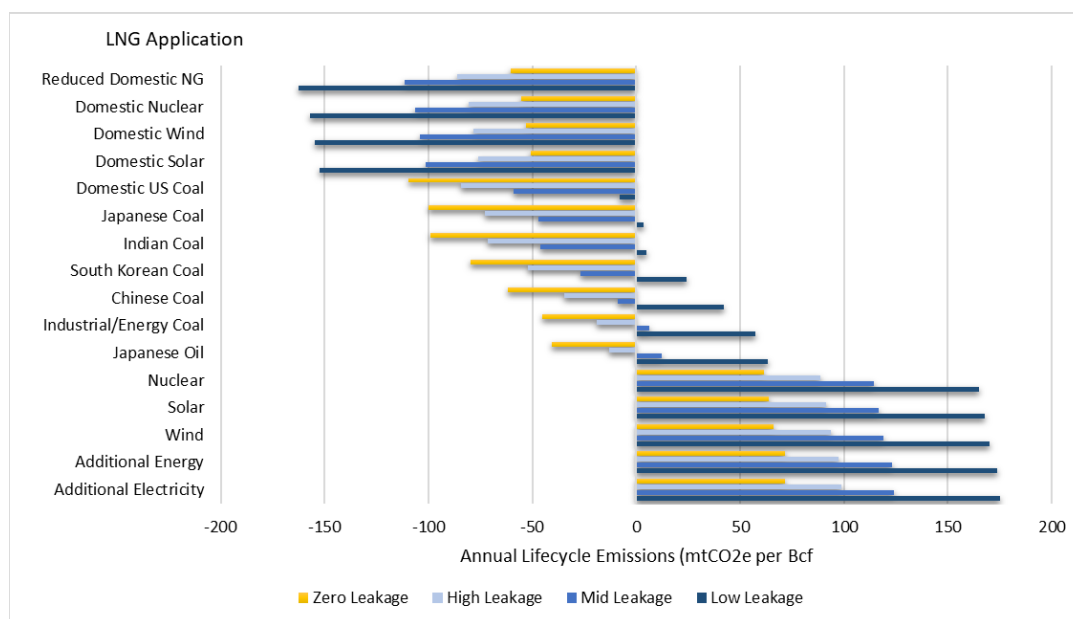
4. Results: Attributional Lifecycle Emissions Estimates

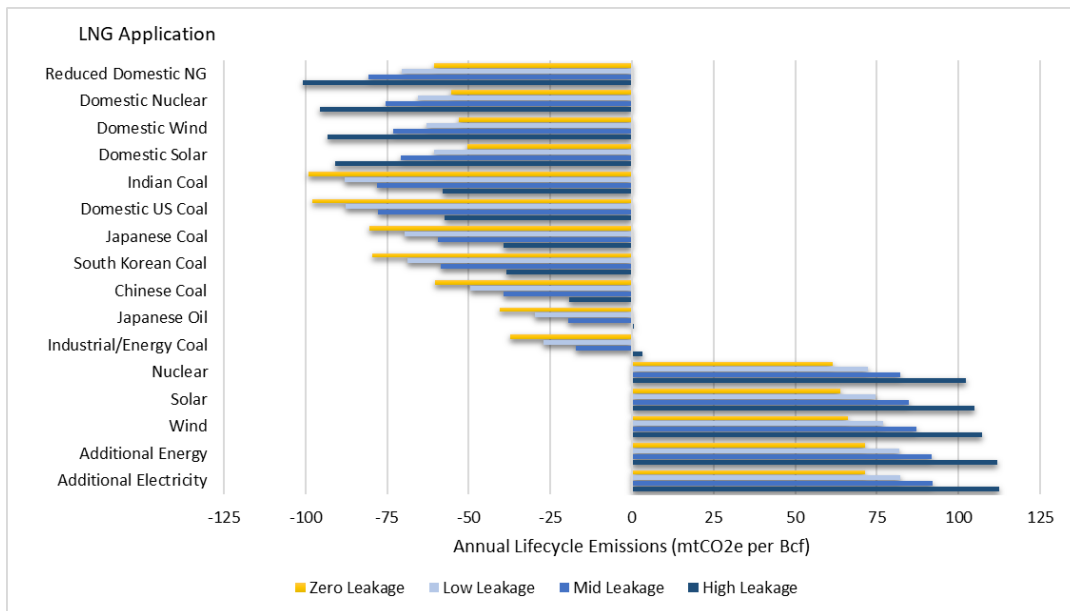
The results of normalizing our aggregated and calculated attributional life cycle greenhouse gas estimates are presented in Table 1. Figure 2 compares the direct emissions change that would occur if LNG came from domestic sources or replaces identified end-uses, with variations based on leakage rate scenarios. In order to quantify both short and long-term climate impacts, we use 20-yr and 100-yr global warming potentials (GWPs).

Table 1. Lifecycle Emissions Factors for Fuel End Uses (100-Yr GWP)

LNG Application	Location	lbs CO2e Emissions/MWh	Source
Coal Generation	United States	2,314	This study
	China	1,970	S. Yu et. al.
	India	2,488	Agrawal et. al.
	South Korea	2,206	K.M. Lee et. al.
	Japan	2,214	H. Hondo
Oil Generation	Japan	1,631	H. Hondo
Coal (heating)	Global	236*	Composite
Nuclear	Global	145	Sovacool
Solar	Global	110	Nugent and Sovacool
Wind	Global	75	Nugent and Sovacool
Natural Gas for Domestic Electricity	United States	1,027-1,460	This study
LNG for Electricity	Importers	1,197-1,631	This study

*Coal for heating is in lbs CO2e/MMBtu HHV

Figure 2. Net Emissions Resulting from Identified Applications of Liquefied Natural Gas**a. 20-Yr GWP**

b. 100-Yr GWP

The potential global net emissions change for an LNG end-use associated with 1 Bcf of LNG exports have a large range depending on the specific end-use and the GWP. At the low end of potential outcomes, replacing Indian coal for electricity would lead to a decrease of 88,000 metric tons of CO₂e using a 100-Yr GWP. On the high end, additional electricity use in importing countries would lead to an increase of 112,000 metric tons CO₂e in the high leakage scenario. There are considerable variations in the benefits of replacing coal for electricity generation from different countries.

Notably, replacing US coal with domestic natural gas has higher benefits than all LNG applications except replacing Indian coal using a 100-Yr GWP. This is due to the emissions associated with liquefying, transporting, and re-gasifying natural gas, as well as the relative inefficiency of the US coal generation fleet. The processes of liquefaction, transportation, and regasification constitute 10-13% of total LNG lifecycle greenhouse gas emissions, meaning that avoiding these emissions by burning natural gas domestically yields large emissions benefits. On

the other hand, using LNG to meet additional price-induced electricity or energy demand had the highest net GHG emissions increase..

Generally, the change in net emissions resulting from different uses of LNG are lower in higher leakage scenarios and when examining short term climate impacts. Any emissions benefit of replacing foreign coal decrease quickly as leakage rates increase and sometimes disappear when looking at 20-Yr GWPs. Importantly, the three uses of LNG with the largest net emissions decreases, replacing Indian, Japanese, or South Korean coal for electricity, are unlikely to occur at significant levels due to each country's energy security goals (as evaluated by Gilbert and Sovacool (2017)) and international obligations of the Paris Agreement.

5. Discussion: Scenario Bounding of International and Domestic Market Outcomes

Using attributional LCA, the above results indicate many potential outcomes from one-to-one replacement by US LNG. However, two dynamic factors shape the final climate impacts of natural gas: outcomes in domestic and international markets. LNG exports could decrease consumption of natural gas in the United States, which would partially be replaced by other electricity sources. Abroad, LNG is likely to both replace other sources of energy and to meet additional energy demand. Our scenario analysis takes these potential factors into account.

When US natural gas prices increased between 2012 and 2013, natural gas generation fell by 110 TWh while coal generation increased by 80 TWh. (37) Exporting LNG could similarly cause gas prices to increase, leading to greater coal generation as a result of coal to gas price competition in regulated and restructured markets.

In 2012 and 2014, the Energy Information Administration (EIA) modelled how various LNG export volumes would impact domestic energy prices and fuel choice. (38, 39) EIA

concluded in both studies that LNG exports would cause prices to rise and decrease natural gas demand in all cases. Between 2015 and 2035, EIA's modelling indicated that new production would meet an average of 65% of exported natural gas while 24% would be served through decreased power sector consumption of natural gas. The remainder would be met by decreased domestic consumption in other sectors. The majority of decreased power sector consumption of natural gas would be offset by increased coal generation.

Importantly, EIA's studies have several shortcomings: they are dated, the full scope of shale resources remains uncertain, EIA's export scenarios may not match eventual export levels, the viability of coal in the United States has declined, and the cost effectiveness of renewable energy has grown greatly. Perhaps most importantly, the future of coal in the United States has changed significantly in the last couple years. A number of high profile enacted or proposed regulations (Mercury and Air Toxics Standards, Cross State Air Pollution Rule, Regional Haze, Clean Power Plan) have led to dramatic decreases in coal generation and large scale retirements. (40)

Accordingly, there is significant uncertainty about what impacts increased exports would have on domestic markets in the U.S. and what it means for emissions. Our domestic market scenarios included the following potential effects: increased natural gas production, decreased natural gas consumption, natural gas replaced by coal, natural gas replaced by nuclear, natural gas replaced by wind, and natural gas replaced by solar. The emissions bounds for domestic impacts were set on the low side by decreased natural gas consumption and on the high side by coal replacing exported LNG for electricity generation.

From a climatic perspective, the domestic opportunity costs of exporting U.S. LNG could have multiple impacts on global greenhouse gas emissions. First, upstream emissions from the

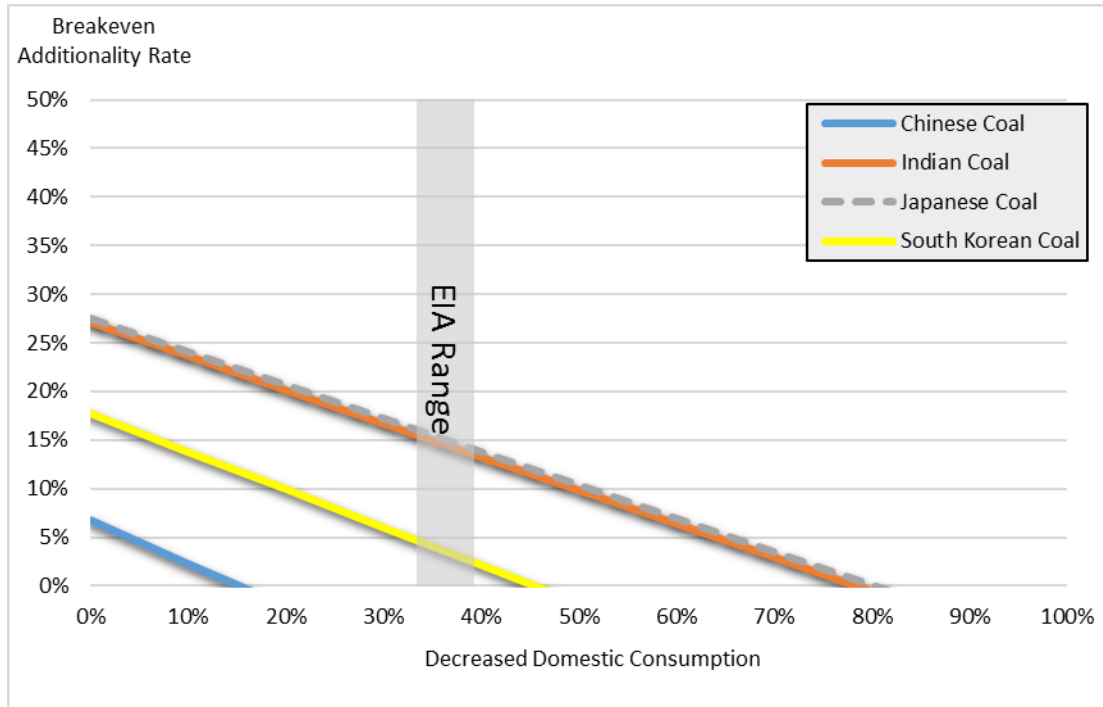
use of LNG compared to domestic consumption are greater due to additional emissions from liquefaction, transport, and regasification. Second, decreased domestic coal to gas fuel switching leads to greater cumulative emissions as coal utilization rises. Third, if LNG drives natural gas prices higher, overall energy consumption could decline. Fourth, despite emissions reductions at a global level, US natural gas production and export can increase domestic emissions if LNG is served by new production or results in increased coal generation.

Internationally, US LNG supplies can increase overall natural gas consumption in importing countries. Greater imports will not just increase use of natural gas for electricity generation, but also natural gas consumption for industrial, residential, and commercial applications. This is an additionality effect: supplies of natural gas are used to provide heating or electricity but do not necessarily displace or replace other sources. This causes additive emissions that could reduce potential emissions benefits from other applications of LNG. Additionality effects on emissions can increase US domestic emissions (per above) but will have a larger impact on emissions from the LNG importer.

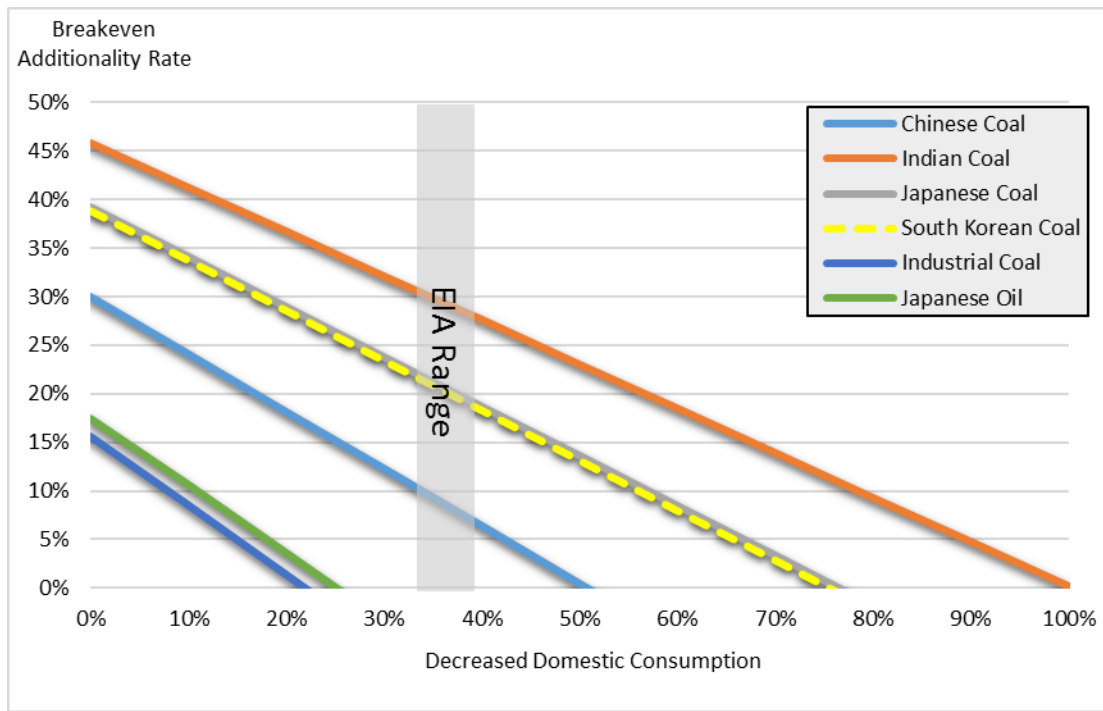
These two dynamic factors, decreased domestic natural gas usage and additional international energy consumption, constrain climate effects from LNG exports. To illustrate these interactions, Figure 3 illustrates the breakeven additionality rate at which lost domestic gas consumption combines with different LNG applications to cause no net change in global emissions, EIA's modelling projects reduced domestic natural gas demand will supply around 34-37% of marginal LNG exports. (39) As most of this is from reducing the replacement of coal by natural gas for domestic electricity generation, the emissions penalties versus LNG applications can outweigh ALCA 1-for-1 benefit estimates.

Figure 3. Breakeven Additionality Rate versus Domestic Consumption of Liquefied Natural Gas

a. 20-Yr GWP



b. 100-Yr GWP



Note: Mid Leakage Scenario.

For example, if 20% of 1 Bcf of LNG exports came from increased domestic coal generation (with the rest from decreased domestic consumption only), then the entire 1 Bcf of exports would need to replace industrial coal for net global emissions to be zero using a 100-Yr GWP. If those same exports were to replace Chinese coal for electricity instead, up to 17% could go to serving additional energy demand for a result of no change in emissions. When the additionality rate is higher than the breakeven level, net emissions are positive and there are negative climate impacts. Only some LNG uses are plotted in Figure 3, as the remaining uses (replacing end-use nuclear or renewables with LNG) would lead to greater emissions regardless of the additionality or domestic displacement rates.

Leakage rates can significantly affect breakeven additionality rates. Figure 3 displays the mid-leakage scenario (3%). In general, the higher the leakage rate, the lower the breakeven additionality rate – the more natural gas leaks, the less additional end-use energy from natural gas is needed to exceed climate benefits. For example, in the 1.5% leakage scenario, 40% of LNG would need to come from increased domestic coal consumption for replacing only industrial coal in order to maintain zero net emissions (as opposed to only 20% in the 3% leakage scenario). Thus, if methane leakage is lower, the tradeoffs between reduced domestic energy consumption and additional international energy consumption become less severe in terms of emissions penalties. Conversely, in the 6% leakage scenario, very few LNG end-use scenarios have a positive additionality rate. In many cases, methane leakage is so high that net global emissions would increase regardless of what happens in the domestic markets. Only coal for electricity generation in importing countries has a positive additionality rate in such a scenario.

A further aggravating factor for coal replacement scenarios is what happens to coal that is displaced by LNG. When LNG replaces coal, 100% of the replaced coal is not matched by a similar decrease in coal consumption. Rather, that coal is available for other uses. Even if most of it is not eventually consumed, some of it is likely to be. This effect is not explicitly accounted for in this analysis, and would lead to higher emissions from coal-related LNG applications, lowering the breakeven rate further. However, the bounding nature of our scenario analysis implicitly accounts for coal that leads to more electricity generation.

The extent of how important the breakeven additionality rate is will depend on the overall levels of LNG exports – more specifically, our scenario analysis only determines domestic and international market impacts on emissions on a rate basis. The final impacts will depend on how much overall U.S. LNG is exported and what it actually replaces.

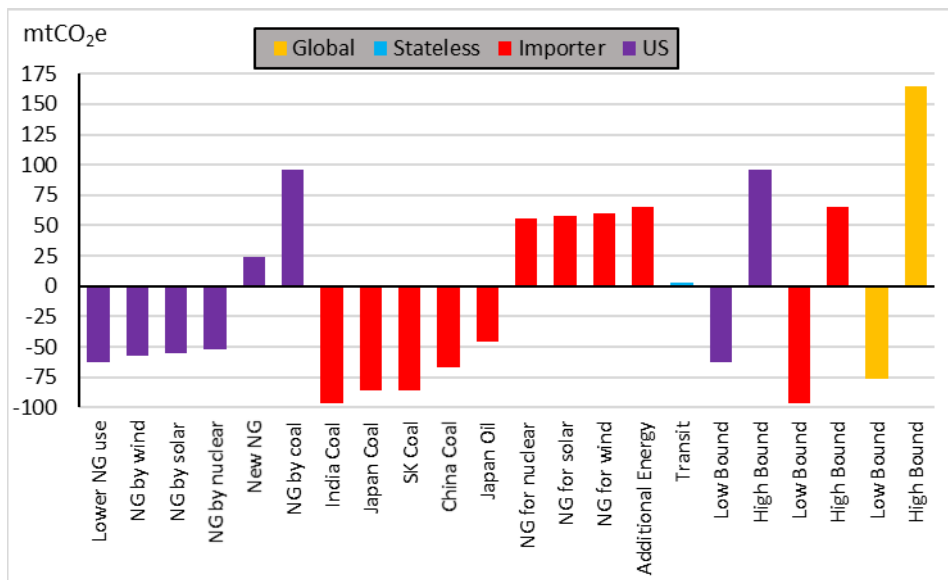
In December 2016, the international community reached a landmark climate deal at the 21st Conference of Parties in Paris, France. The subsequent accord, the Paris Climate Accord, requires countries to submit Intended Nationally Determined Contributions (INDCs) to reduce their greenhouse gas emissions. Each country in this analysis has developed and submitted an INDC pledge; however, the U.S. has since indicated its desire to leave the agreement. These pledges, could greatly influence market and emissions outcomes from increased U.S. LNG exports to Asia:

1. China has pledged to peak its carbon dioxide emissions by 2030 (at the latest), low CO₂ GDP intensity 60-65% from 2005 levels, and to increase the share of non-fossil fuel energy consumption to 20%. (41)
2. The United States initially pledged to reduce its economy-wide greenhouse gas emissions by 26-28% below 2005 levels by 2025. (42)

3. India plans to install 175 GW of renewable capacity by 2020, reduce GDP emissions intensity 33-35% below 2013 levels by 2030, and increase the share of non-fossil power capacity to 40% by 2030. (43)
4. Japan pledged to reduce its emissions 26% below 2013 by 2030. (44)
5. South Korea plans to reduce economy wide emissions 37% below business-as-usual forecasts by 2030. (45)

A global climate agreement can complicate both global emissions reductions efforts and attempts to quantify LCA impacts of energy export projects. Critically, the decision of the US to leave the Paris Agreement creates the possibility of emissions leakage from covered countries to the US. To put another way, energy exports can increase the exporter's extraction or production emissions while reducing importer's production emissions.

Figure 4. National and Global Level Emissions Outcomes of Liquefied Natural Gas Scenarios, per Bcf



Accordingly, Figures 4 quantifies US, importer, non-national, and global emissions outcomes in each of our import and export scenarios using the low leakage scenario. Three

things of note. First, a small portion of global emissions ($\sim 3 \text{ m}_t\text{CO}_2\text{e}$ per Bcf) in export scenarios occurs in international waters and is thus stateless and not subject to Paris restrictions. Second, net emissions outcomes for the US and importer emissions can differ significantly from each other. Exports could cause US emissions to rise while increasing importer emissions, or vice versa. Third, global emissions outcomes can differ significantly from outcomes in either the exporting US or importing countries. Together, these factors indicate that exporting LNG could cause major leakage issues if the United States leaves the Paris Agreement.

6. Conclusion and Policy Implications

A bounded scenario lifecycle approach that considers likely uses of US LNG and importing country-specific emissions profiles for Asian importers indicates that exporting LNG has uncertain but potentially large global climatic consequences. Importantly, our scenario bounds indicate that, contrary to the conclusions from Skone et. al and Abrahams et. al., the directional effect of U.S. LNG exports to Asia on global emissions is highly uncertain – it could cause global emissions to decrease or increase substantially. Key data, policy, technology, and market uncertainties lead to a very large range of potential emissions outcomes, as do methane leakage rates. In light of this large range and these uncertainties, we offer three conclusions.

First, a bounded scenario analysis can provides an informative look at the potential global emissions affects of country-level export scenarios. By using a combination of attributional LCA and international and domestic market scenarios, the potential emissions outcomes from a unit of export can be bounded within a specific range. Examining potential international and domestic market scenarios within these bounds provides a key first step in constraining the uncertainties

and challenges of estimating emissions from exports. With major uncertainties, our bounded approach can inform subsequent analysis for export scenarios.

Second, further research is needed into key uncertainty factors that will shape exactly how U.S. LNG exports will impact global greenhouse gas emissions. Admittedly, a lack of quality lifecycle emissions information for Asian importers and uncertainty regarding market impacts creates significant data quality challenges. While our study identifies these uncertainties and concerns, additional research is needed to understand how they will impact emissions outcomes from exports. Key factors underlying uncertainty in the large range of emissions outcomes that this study bounds include:

- The overall level of exports;
- Type of end-uses in importing countries;
- The mix of import uses;
- Effects on U.S. domestic emissions;
- The methane leakage rate;
- Each country's energy policy.

On the lifecycle side, further research should improve the quality of lifecycle emissions of generating assets in Asia, examine the lifecycle emissions of smaller LNG end-uses like cooking or vehicle use, determine lifecycle emissions for alternative natural gas sources (such as other LNG or local natural gas resources), and should more thoroughly examine temporal emissions impacts. Further research should also look into key market uncertainties, such as the demand elasticity of LNG demand in Asia, identify the market impacts of increased LNG availability,

and domestic market impacts in the U.S. from increased natural gas exports. Finally, in light of the Paris Accord, further research should examine how LNG can either help or hinder countries reach their INDC pledges as well as the potential for emissions leakage from the US leaving the Accord.

Third, in light of these uncertainties, policymakers in the United States and abroad must more fully consider the complete climate ramifications of LNG exports. The existing literature to date only provides a limited picture of the potential emissions outcomes. Although the U.S. does not have direct control over the emissions resulting from combustion of exported LNG in other countries, it faces the critical policy decision of whether to allow such exports in the first place in light of ongoing policy initiatives to limit climate emissions. Our study suggests that exports could increase US domestic emissions regardless of impacts on net global and importer emissions. In addition, our study demonstrates that fossil fuel export emissions are exceedingly complex to calculate with either a traditional attributional or consequential life cycle assessment. Nevertheless, these results may better inform policy makers of ongoing uncertainty and real world implications.

Based on our results, policymakers could use LNG exports as a useful climate mitigation technique if methane leakage is minimized, LNG is sourced from reduced domestic consumption, and LNG replaces primarily coal for electricity generation. However, going in the opposite direction towards a large net carbon source is also possible—if methane leakage remains unaccounted for, if LNG is not sourced from domestic consumption, and if it does not replace coal for electricity generation. Thus, how gas is governed (and regulated) becomes of critical importance.

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8. Appendix I

Using the criteria of accepting studies that covered specific existing power plants, we were only able to identify one lifecycle greenhouse gas estimate each for Japanese coal, Japanese oil, South Korean coal, and Indian coal. (35-37) While we were able to identify more estimates for Chinese coal, a lack of standardization and unclear data sources led to us excluding all but one study. (38)

Due to the many potential domestic and international GHG sources covered, our ALCA estimates ended up using different boundaries. To the extent possible, these greenhouse gas estimates were harmonized to include similar emissions categories. However, it was not possible to do so with all estimates. In particular, nuclear and renewable energy ALCA estimates were based on very different components (reflecting that their emissions primarily come from construction, not combustion). Notably, all of our coal estimates included information about coal mine emissions and thermal efficiency, which Whitaker et.al. indicate may be sufficient to encompass overall lifecycle emissions estimates. (23)

In order to calculate the emissions profile of thermal coal, we assumed that upstream emissions equaled the average upstream emissions of the four coal generation types.

We also included lifecycle greenhouse gas estimates for nuclear, solar, and wind. Our rationale for including these sources was that increased LNG use or availability could impact country decisions to adopt these sources. For example, until very recently, high LNG prices were primary drivers of Japan adopting solar PV and were a potential motivation to restart the nation's nuclear fleet. Additional U.S. LNG could lower LNG prices in these studied countries and thus lead to reduced nuclear, wind, or solar generation. We adapt the average emissions estimates for these sources from Sovacool (2008) and Nugent and Sovacool (2014). (39, 40) The boundaries

from these estimates vary from ones used for fossil fuels and more fully reflect emissions for the fuel cycle for nuclear and renewable sources. As there is limited LCA emissions differences for these categories, we treated international and domestic nuclear and renewable energy as having the same LCA profile.

Natural gas lifecycle emissions estimates were estimated by developing a life cycle emissions model that included the following categories: combustion, liquefaction, transportation, regasification, and upstream methane leakage. Combustion emissions were assumed to equal the combustion emissions from a new combined cycle facility. (41) Transportation emissions were developed from Hondo. (37) Methane leakage from natural gas operations were treated as a major uncertainty and are described below.

In order to gauge the potential impacts of increased LNG markets on domestic U.S. coal markets, we needed an estimate of emissions from domestic U.S. coal. In order to develop such an estimate reflective of the average U.S. coal plant, we calculated average combustion and coal mine methane emissions based on data from the EPA and EIA. (42, 43) This method uses real world data to calculate the main parameters influencing coal ALCA estimates. We choose this method due to high data quality and a desire to model the ‘average’ U.S. coal plants. Many other studies have examined drivers and uncertainty behind coal emissions. (44, 45) However, none of these studies accounted for the unique mix of coal mine types in the U.S. (underground and mountaintop removal) which leads to a unique coal mine methane profile. Rather these studies treated different mine types as a source of variability. Calculating our own estimates based on blended averages is more representative of a typical U.S. coal plant. To account for upstream emissions that are not from coal mine methane, we adapted an estimate from Alvarez et. al. (12) Overall, these non-CMM upstream emissions were a tiny portion of the overall domestic coal

LCA. Our LCA emissions estimates for domestic U.S. coal are consistent with other coal LCA estimates that we reviewed.

To the extent possible, all lifecycle emissions estimates were normalized to Global Warming Potentials (GWPs) from the most recent IPCC 5th Assessment. However, given data limitations from emissions estimates, the only emissions estimates that were fully able to be normalized were U.S. LNG exports and Chinese coal generation. As methane constitutes a higher proportion of lifecycle emissions from natural gas combustion, being able to use the most up to date estimates for U.S. LNG is beneficial. However, the inability to adjust methane GWP estimates for other sources likely leads to our numbers for other coal sources being lower than they would actually be (especially for a 20-yr GWP). The practical effect of this is that the emissions benefits of replacing coal generation in Indian, Japan, and South Korea may be somewhat understated. While more fully normalizing the data would be ideal, the practice of accepting published data is an established practice in the energy studies field. (23, 39, 40).

Finally, we did not evaluate alternative natural gas supplies due to a lack of sufficient data about alternative supplies and because the emissions changes from gas to gas replacement are small. As noted in the introduction, other studies have evaluated the LCA emissions of LNG exports from other countries. The primary differences in our estimates of LCA emissions would be due to: different domestic natural gas production sources and emissions, different methane leakage rates (of which there is insufficient international data available), differences in liquefaction efficiency, and differences in transportation distances (which are a minor factor).